

# The P-wave velocity structure of the crust–mantle transition zone in the continent of China

Ge Lin<sup>1</sup> and Yanghua Wang<sup>2</sup>

<sup>1</sup> Key Laboratory of Marginal Sea Geology, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

<sup>2</sup> Department of Earth Science and Engineering, Centre for Reservoir Geophysics, Imperial College London, London SW7 2AZ, UK

E-mail: [gelin@gig.ac.cn](mailto:gelin@gig.ac.cn) and [yanghua.wang@imperial.ac.uk](mailto:yanghua.wang@imperial.ac.uk)

Received 20 May 2005

Accepted for publication 28 July 2005

Published 22 August 2005

Online at [stacks.iop.org/JGE/2/268](http://stacks.iop.org/JGE/2/268)

## Abstract

The crust–mantle transition zone (CMTZ) is an important site for mass and energy exchange between the lower crust and the upper mantle. Several types of CMTZ show different P-wave velocity structures corresponding to different rock associations existing beneath the continent of China. (a) The CMTZ beneath the Tibet Plateau exhibits a grid-shaped seismic reflection characterized by random and reticular high and low seismic velocity lamellae. This seismic velocity structure (about 30 km in thickness) was inherited from crustal overthrust and overlapping during the Cenozoic collision between the Indian and Euro-Asian continents. The corresponding crustal movement is still very intense in this region. (b) The CMTZ underneath East China is usually composed of a thinner, strong positive velocity gradient layer. It suggests that the crust is still active in East China after significant lithospheric thinning and thermal accretion. (c) The CMTZ in the tectonic stable regions is characterized by a relatively sharp seismic discontinuity. Such a feature beneath the Ordos basin corresponds to weak crustal movement after a long period of isolation from thermo-tectonic overprinting.

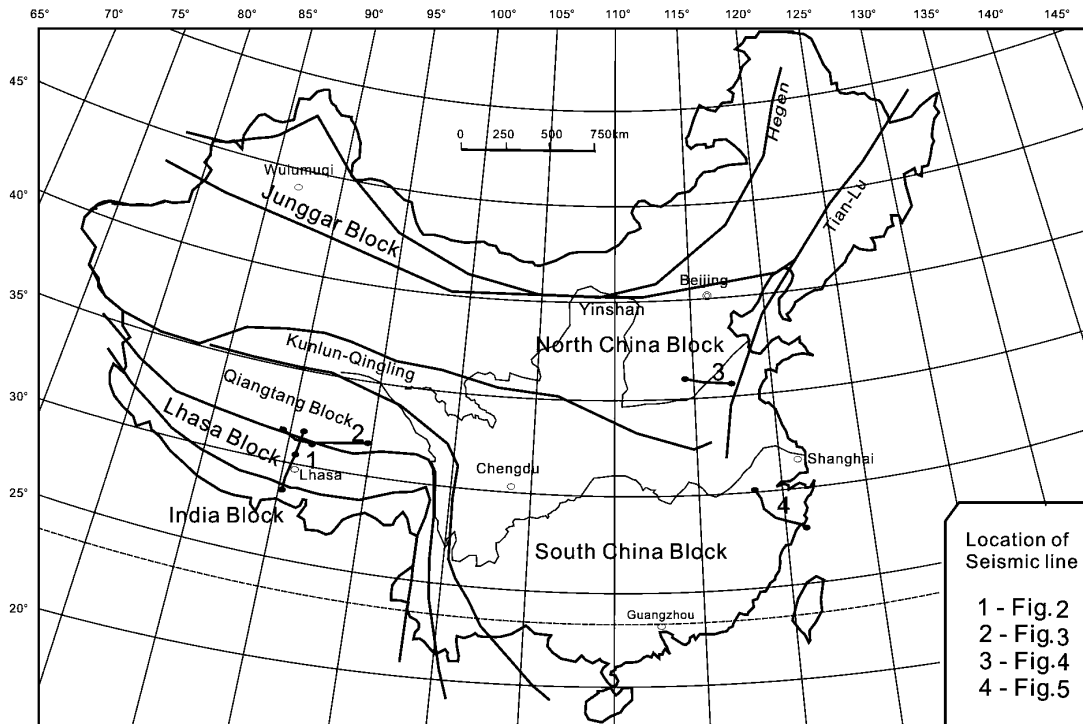
**Keywords:** velocity structure, crust–mantle transition zone (CMTZ), continent of China

## 1. Introduction

The seismic profiles and petrologic studies show that the lower crust–upper mantle boundary (the Moho) of continental lithosphere is not a simple geometrical boundary: usually a so-called crust–mantle transition zone (CMTZ) develops, in which the mass and energy exchange takes place (Boudier and Bouchez 1980, Hauser *et al* 1987, Jarchow and Thompson 1989, Hall *et al* 1990, Snyder and Flack 1990, Owens and Zandt 1997, Sandvol *et al* 1997, Stefano *et al* 1999, Carbonell *et al* 2002, Peter and Sierd 2004). Studies of deep-seated mantle and lower crust xenoliths have also identified different kinds of CMTZ beneath continental plates as an indicator for crustal movement (Ringwood 1975, Sandmeier *et al* 1988, Christensen 1989, Mooney and Meissner 1992, Cox *et al* 1993, Menzies *et al* 1993, Durrheim and Mooney 1994,

Royden *et al* 1997, Alsdorf *et al* 1998, Cogan *et al* 1998, Curtis *et al* 1998, Meissner and Mooney 1998, Melhuish *et al* 2005).

The wide range of P-wave velocities ( $V_p = 7.2\text{--}8.0\text{ km s}^{-1}$ ) of the CMTZ implies a complexity in its composition. Experimental petrologic data (e.g., Holbrook *et al* (1992)) show that the  $V_p$  range of  $6.4\text{--}7.2\text{ km s}^{-1}$  of the lower crust is consistent with the measured  $V_p$  of felsic to mafic granulitic rocks under similar pressure–temperature conditions. This is mostly the case for the predominant rock associations of the lower crust. The  $V_p$  range of  $7.2\text{--}8.0\text{ km s}^{-1}$  representing the CMTZ corresponds to mafic to ultramafic granulites according to experimental data, such as mafic granulites, pyroxenites as well as a certain amount of peridotites. When  $V_p$  is up to or greater than  $8.0\text{ km s}^{-1}$ , the inferred rock types should be typical of an upper mantle assemblage including dunites, lherzolites and eclogites.



**Figure 1.** The locations of seismic survey lines shown in this paper.

Deep-seated xenoliths from the lower crust and the upper mantle entrained in alkaline basalts, kimberlites and lamproites directly provide the rock type and chemical compositions of the CMTZ. Griffin and O'Reilly (1987) noted that the lower crust commonly consists dominantly of intermediate rocks and mafic rocks whilst mafic granulites predominant in continental rifts and mobile orogenic belts, where a dual characteristic in rock assemblage within the CMTZ can be observed: the predominant mafic granulites of the lower crust and ultramafic rocks of the upper mantle are mixed together with decreasing proportion of mafic rocks towards the mantle (e.g. Fountain and Salisbury (1981), Fountain *et al* (1990), Willett and Beaumont (1994), O'Reilly and Griffin (1996), Ge *et al* (1999), Joussetin and Nicolas (2000), Chen *et al* (2001) and Hermann *et al* (2001)).

In this paper, we discuss the P-wave velocity structure of crust–mantle transition zones in the continent of China and its significance for the tectonics of the region. We consider three types of CMTZ associated with the following three different areas: the Tibet Plateau, East China and tectonic stable regions (i.e. continental platform or shield areas) such as in Ordos and Sichuan basins.

## 2. The CMTZ in the Tibet Plateau

### 2.1. The P-wave velocity structure

It is believed that the CMTZ usually exists beneath the tectonically mobile regions, such as orogenic belts and tectonically remobilized continents. The first type of CMTZ is representative of the Tibet Plateau (figure 1) where the P-wave

velocity profiles are as shown in figures 2 and 3. Underneath this area, the CMTZ is about 30 km thick with an identically shaped top lying at a depth of 50–60 km, and a flat base at a depth of 70–80 km with an average  $V_p$  of about  $7.4 \text{ km s}^{-1}$  (Teng *et al* 2003). The inner part of the CMTZ is composed of alternating thin, sub-horizontal, random high- and low-velocity laminae.

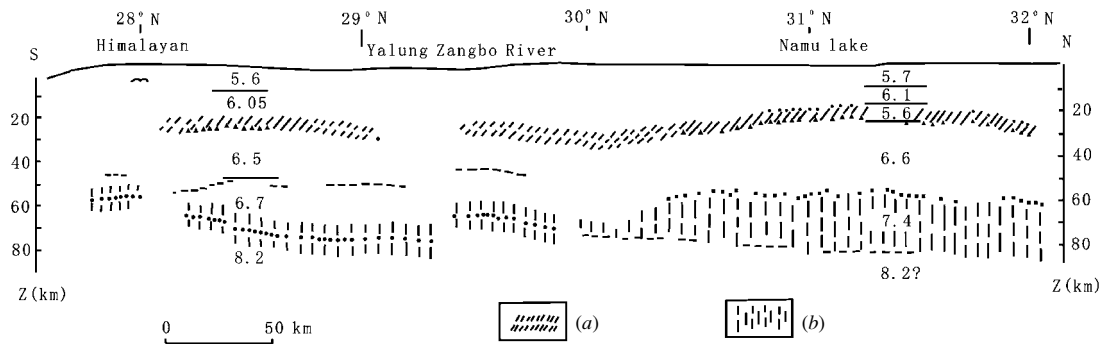
The P-wave velocity structure of the CMTZ beneath the Tibet Plateau coincides approximately with the fine seismic transect model proposed by Wenzel *et al* (1987). The CMTZ including the base of the lower crust could be horizontally continued and pursued in the seismic transects, and the distribution and thickness of the laminae are random. In some cases, the CMTZ is not the strongest reflector in the seismic transect, while the lower crust displays stronger reflection.

### 2.2. Petrological properties

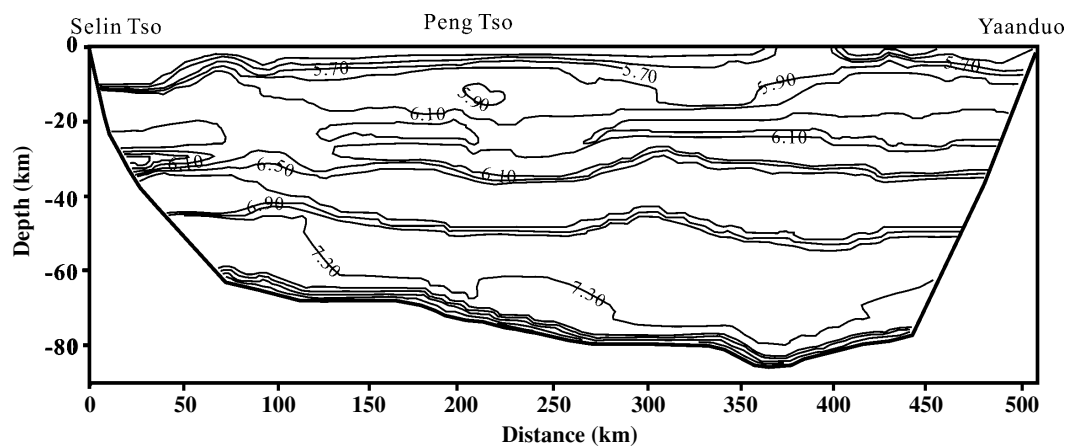
Seismic studies beneath the Tibet Plateau show that the crust is composed of the upper, middle and lower crust, corresponding respectively to greenschist-, amphibolite- and granulite-facies rocks, and a crust–mantle transitional layer of about 30 km thickness between the lower crust and the upper mantle.

According to experimental data, there are two kinds of reactions for mafic granulites under lower crustal conditions (Holloway and Wood 1988):

- (1) when  $T = 400\text{--}800 \text{ }^\circ\text{C}$  and  $P = 10\text{--}12 \times 10^8 \text{ Pa}$  (equal to a depth of 35–40 km), orthopyroxene will disappear and the rocks will be transformed into high- $P$  granulites;
- (2) when  $T = 400\text{--}800 \text{ }^\circ\text{C}$  and  $P = 12\text{--}18 \times 10^8 \text{ Pa}$  (equal to a depth of 45–60 km), plagioclase will disappear and



**Figure 2.** A N-S-trending seismic transect in the northern Dangxiong area, Tibet (line 1 in figure 1). (a) lower velocity layer in the crust. (b) The crust/mantle transition zone.



**Figure 3.** A W-E-trending P-wave velocity profile in the Tibet (line 2 in figure 1).

the rocks will be further metamorphosed into high- $P$  eclogites.

Considering the regional seismic reflection results, it is likely that the crust–mantle transitional layer beneath the Tibet Plateau is mainly composed of high- $P$  granulite-facies rocks, eclogites and minor spinel lherzolites. The uppermost mantle comprises mainly spinel-garnet lherzolites, dunites and garnet lherzolites as well as minor eclogites and pyroxenites.

### 2.3. Tectonic evolution

In the Tibet Plateau, the Cenozoic (starting at 40 Ma) collision between the Indian and Euro-Asian continents took place after the final closure of the Neo-Tethyan Ocean. Following oceanic closure and continental collision, multiple crustal (sometimes the upper mantle or the overriding slab) overthrusting and overlapping at different levels resulted from plate constriction and formed the extremely thick crust under the orogen. The mixing of different parts of the lithosphere between the lower crust and the upper mantle makes the rock association in the CMTZ complex, just as those tectonic mélanges in the collisional suture. The large thickness of the crust (70–80 km) and the CMTZ (about 30 km) is gravitationally unstable and the mass and energy exchange is still active. This is in good agreement with the intense volcanism and frequent earthquakes currently observed in the region.

## 3. CMTZ in East China

### 3.1. The P-wave velocity structure

The second type of CMTZ in the P-wave velocity profiles is characterized by a strong positive velocity gradient zone and can be found in East China (see figure 1). Figure 4 shows that, beneath the Anyang (Henan Province)–Sishui (Shandong Province) area, the P-wave velocity  $V_p$  increases rapidly from 7.2 km s<sup>-1</sup> up to 8.0 km s<sup>-1</sup>, suggesting a transition from the lower crust to the upper mantle. The thickness of the CMTZ in the depressed region is about 2 km and the P-wave velocity increment is up to 0.2–0.5 km s<sup>-1</sup> per kilometre downwards. In the neighbouring (uplifted) regions, the CMTZ range is 3–5 km thick and only a P-wave velocity increment of 0.05–0.1 km s<sup>-1</sup> is observed. Similar velocity structure of the crust is also observed in the Shuijiangzhao–Kazhishenqui deep seismic transect, which has a strong positive velocity gradient layer of 1.5 km thickness between the lower crust and the upper mantle. The velocity gradient in the depression region is 0.47 km s<sup>-1</sup>, while it is 1.4 km s<sup>-1</sup> in the northern mountainous regions (Zhang *et al* 2000a). This kind of strong positive velocity gradient layer is prevalent beneath the eastern North China block, e.g., in the Tanshan and Beijing areas.

This type of CMTZ, constituted by the positive velocity gradient zone but with variable thickness, can also be found in other regions of the East China. The P-wave velocity

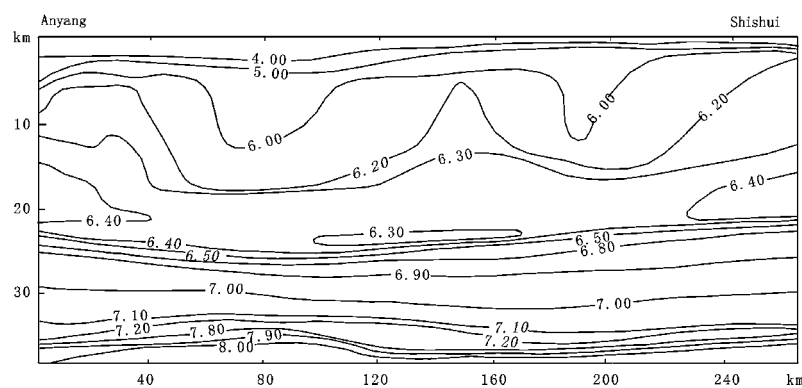


Figure 4. The P-wave velocity profile (W-E trending, Anyang–Shushui seismic transect) in North China (line 3 in figure 1).

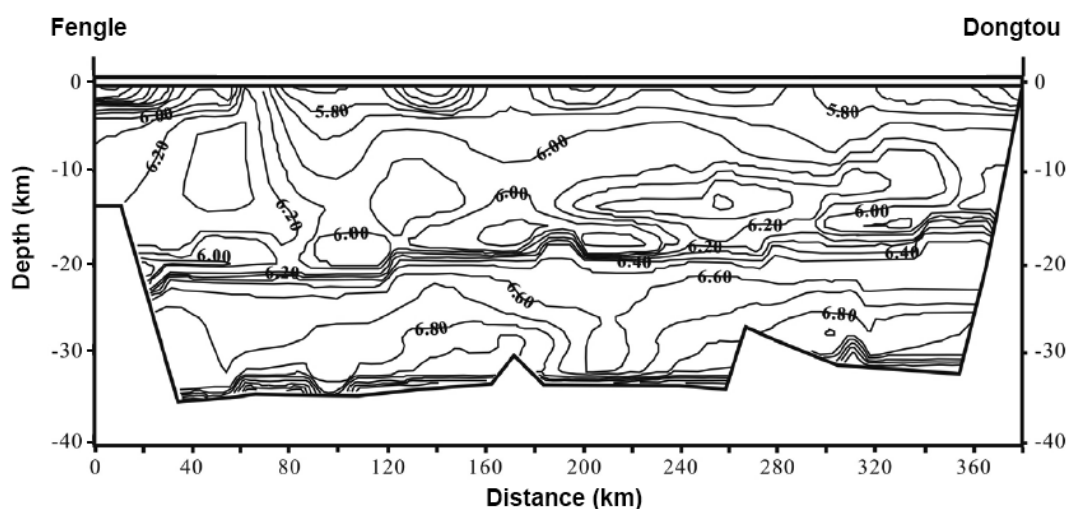


Figure 5. The P-wave velocity profile (W-E-trending Fengle–Dongtuo seismic transect) in South China (line 4 in figure 1) (after Zhang *et al* (2005)).

profile (W-E-trending Fengle–Dongtuo seismic transect) in South China (figure 5) shows that, using a strong energy and wide-angle seismic method, there is a strong positive velocity gradient zone. There are several reflector discontinuities in the crust, where nearly all horizontal reflectors are mainly in the lower crust (with depth more than 15–20 km). One of the interesting aspects is that there are numerous thin reflection layers within the upper crust, and the reflectors previously interpreted are not really abrupt discontinuities, but instead are transition zones with a thickness of 2–3 km; another is that though the depth to the top of the Moho is similar to the previous result, the Moho transition zone consists of several thin layers with a total thickness of 2–3 km. Meanwhile, there are still many horizontal reflectors beneath the Moho (Zhang *et al* 2000b). The reflection amplitudes observed from the crust–mantle boundary are sufficiently large to suggest that there is no significant partial melt in the deep crust. There are, however, multiple refracted P<sub>n</sub> and S<sub>n</sub> phases clustered after the P<sub>m</sub> and S<sub>m</sub> arrivals. We interpret that this is due to irregular scattering from the Moho; that is, the crust–mantle boundary is not a simple discontinuity in velocity but a transition zone enhanced by a strong velocity gradient. In effect, we observe at 2–3 km a sharp variation in the

P-wave velocity from 7.4 to 7.8 km s<sup>-1</sup> to the northwest and from 7.4 to 8.0–8.2 km s<sup>-1</sup> to the southeast. The top of the lithospheric mantle features a sharp lateral variation in P- and S-velocities, which is approximately beneath Songyang. The crust is gradually thinner from the northwest to southeast due to the irregular topography of the Moho (Zhang *et al* 2005). The crustal structure in the eastern Guangxi Province reflects that there is a strong positive velocity gradient layer of 6.5 km thickness just overlying the upper mantle revealed by both the wide-angle seismology and travel time hyperbola methods.

### 3.2. Petrological properties

A strong positive velocity gradient layer with the  $V_p$  value of 7.2–8.0 km s<sup>-1</sup> is commonly present between the lower crust and the upper mantle in East China (including the North and South China blocks). Experimental studies in this region indicate that besides the mafic augite–granulite, the clinopyroxene + augite + anorthoclase + garnet assemblage in the Cenozoic basalts is also an important contribution to the CMTZ. It has been suggested that the mafic granulite spans a  $V_p$  range of 7.2–7.4 km s<sup>-1</sup> and about 7.8 km s<sup>-1</sup>

for gabbro and about  $8.2 \text{ km s}^{-1}$  for spinel lherzolite. It is thus reasonable to conclude that mafic granulites and gabbros are the important components in the CMTZ. On the other hand, numerous previous studies on basalt-borne xenoliths found that the uppermost mantle beneath the North China Block is predominantly composed of spinel lherzolite with minor garnet peridotites (Fan *et al* 2000, Chen *et al* 2001). In this respect, the estimated rock assemblage in the CMTZ should also include some amount of spinel lherzolite to account for the  $V_p$  variation from  $7.2$  to  $8.0 \text{ km s}^{-1}$ .

### 3.3. Tectonic evolution

In East China, significant lithospheric thinning occurred during the Mesozoic–Cenozoic (Menzies *et al* 1993, Griffin *et al* 1998, Fan *et al* 2000, Guo *et al* 2001, 2003), triggering strong modification of the crustal structure (Lin *et al* 2004, Wang *et al* 2005). Due to basaltic underplating and mantle accretion following lithospheric extension, the CMTZ in the area is composed of underplated basalts, Archean granulites and newly accreted and residual aged mantle fragments. The strong positive  $V_p$  gradient in the seismic profile is caused by the replacement of the lower crust and upper mantle in response to the lithospheric thinning event. Compared with that beneath the Tibet Plateau, the mass and energy transfer is less active and the crustal movement is dominated by faulting and rifting as in the Basin and Range Province of the United States.

The CMTZ underneath East China is usually composed of a thin layer of strong positive velocity gradient with dual properties in the rock associations, composed of mafic granulites and spinel lherzolites. The crust is still active in East China after significant lithospheric thinning and thermal accretion.

## 4. CMTZ in the tectonically stable regions

### 4.1. The P-wave velocity structure

The third type of CMTZ shows a clear leap in the P-wave velocity between the lower crust and the upper mantle (considered as the theoretical Moho plane) in the continent of China. It is seen in tectonically stable regions, i.e., continental platform or shield areas such as in the Ordos and Sichun basins (Teng *et al* 2003).

### 4.2. Petrological properties

The sharp leap of  $V_p$  from  $7.2 \text{ km s}^{-1}$  to  $8.0 \text{ km s}^{-1}$  suggests the absence of CMTZ in the deep seismic transect in the Ordos basin: this suggests a clear boundary between the lower crust and the upper mantle. Due to long-term isolation from thermo-tectonic overprinting in the Ordos basin, the mass and energy transfer between the lower crust and the upper mantle is weak, consistent with inactive crustal movement and rare earthquakes.

## 5. Discussion and conclusion

### 5.1. The variety of wave velocity structure in the CMTZ

In general,  $V_p$  increases with depth with multiform styles, such as homogeneous, ladder-like and interlaced high–low velocity structures, increasing, reflecting the complexities of the rock combinations in the CMTZ. The thickness of the CMTZ varies: in stable cratonic zones (platforms) it is 300–500 m thick and the Moho is easy to identify; in old orogenic belts it is 2–5 km, 3–5 km in continental rift zones, 10–20 km in young orogenic belts and 20–30 km in uplifted plateau areas where the wave velocity gradient is low ( $0.05$ – $0.1 \text{ km s}^{-1}$ ). The thickness of CMTZ is the midterm value in zones between stable and active parts, which reflects the obvious transverse inhomogeneity in the crust. It is found that the bottom surface of CMTZ is not straight in Tibet and some young continental orogenic belts: some stagger faults and superposition phenomena appear together, which indicates interweaving between the lower crust and upper mantle (Deng and Zhong 1997).

The variety of wave velocity structure in the CMTZ in different structural regions reflects the characteristic rock combinations and patterns of heat condition and transfer in those regions. It is therefore important to understand the continental dynamic process.

### 5.2. Three types of CMTZ in the continent of China

In this paper, we classify the CMTZ of the Chinese continent into three types, which exhibit distinguishable seismic characteristics and lithological associations, as summarized in figure 6. The first type, such as in the Tibet Plateau, a Cenozoic collisional belt, has a relatively high thickness, consisting of many thin layers of alternating high and low velocity. The second type, such as in East China, a tectonically remobilized continental block undergoing significant lithospheric thinning, has a relatively low thickness with strong positive velocity gradient. The third type, appearing in tectonically stable regions such as the Ordos, is a clear lithological boundary with a sharp velocity discontinuity. The petrologic structural sections of these three CMTZ types are also constructed in figure 6, in combination with results from deep-seated xenoliths and experimental petrology.

Three types of CMTZ in the continent of China are identified on the basis of the P-wave velocity profiles, petrologic results of deep-seated xenoliths and experimental petrology. Different CMTZ types in different tectonic regimes correspond to the current crustal movement characteristics.

- (1) The Tibet Plateau, which has the thickest crust on Earth, has a CMTZ of about 30 km thickness. The CMTZ beneath the orogen exhibits a grid-shaped seismic reflection, characterized by random and reticular high and low seismic velocity lamellae, comprising both mafic granulites of the lower crust and ultramafic rocks of the upper mantle. Such a lithological association and seismic velocity structure were inherited from the crustal overthrust and overlapping during the Cenozoic collision

Area	Types of CMTZ	Section Map*	Petrological Structure
Tibet			Up.c: Sedimentary, greenschist+granite
			M.c: Hornblende-facies granulite
			Lo.c: High-P granulite-facies eclogites and minor spinel lherzolites
			CMTZ: Spinel-garnet lherzolites, dunites and garnet lherzolites as well as minor eclogites and pyroxenites, granulite-facies rocks
East China			Up.c: Sedimentary, greenschist+granite
			M.c: Hornblende-facies granulite
			Lo.c: Mafic granulite garnet-anorthoclase-augite cumulus
			CMTZ: Mafic granulite, gabbro, peridotite, garnet lherzolite
Ordos			Up.c: Sedimentary, greenschist+granite
			M.c: Hornblende-facies granulite
			Lo.c: Acidic granulite+eclogite, biotite-feldspar gneiss
			Up.m: Spinel facies-peridotite, dunite, lherzolite

Figure 6. The geophysical and lithological features of three types of CMTZ in the continent of China (\*according to Zhang *et al* (2003)).

between the Indian and Euro-Asian continents. The corresponding crustal movement is still very intense in this region.

- (2) The CMTZ underneath East China is usually composed of a thin layer of strong positive velocity gradient with dual properties in the rock associations composed of mafic granulites and spinel lherzolites. The crust is still active

in East China after significant lithospheric thinning and thermal accretion.

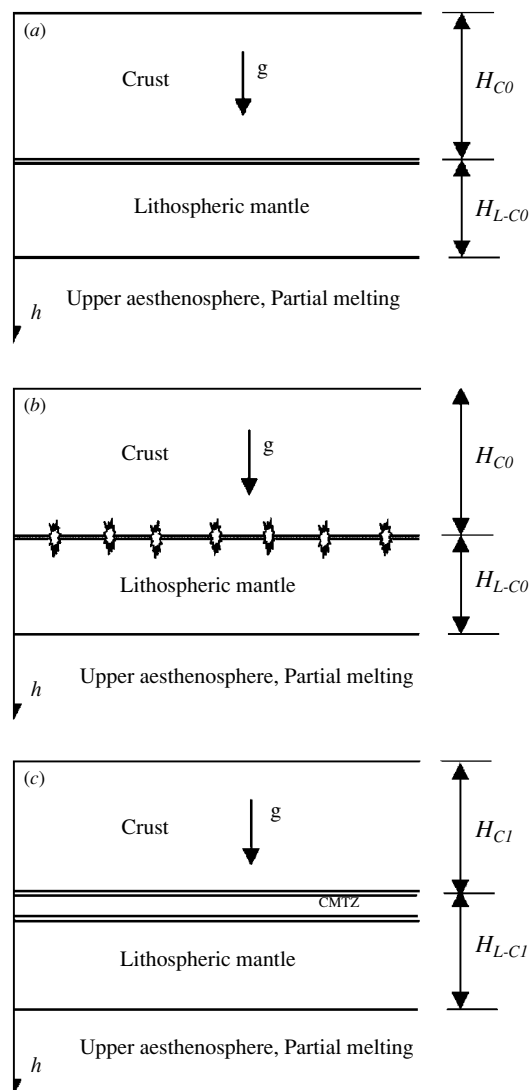
- (3) The CMTZ in the tectonically stable regions is characterized by a relatively sharp seismic discontinuity and a clear lithological boundary between the lower crust and the upper mantle. This feature of the CMTZ beneath the Ordos basin corresponds to the weak crustal movement

after a long period of isolation from thermo-tectonic overprinting.

### 5.3. Possible formation pattern of the CMTZ

Both geochemical data from rocks in the upper mantle and lower crust, and geophysical observation show that the CMTZ exists in intercontinental regions. The formation mechanism is discussed through different facets. One possible formation pattern of the CMTZ is the generation of a 'crust–mantle mixed layer' through heating by upwelling of asthenosphere material and partial melting. Abundant xenoliths, megacrysts and pyroxene veins in the east of China provide evidence that lithospheric mantle materials moved towards crust, which is related to Mesozoic–Cenozoic lithospheric thinning in the east of China (Xu *et al* 1996, Xu 2001). Accompanied by lithospheric thinning, the asthenospheric materials and energy injected into the lithosphere lead to lithospheric structural instability and rapid geotemperature gradient increase, resulting in extensive melting of asthenosphere, lithospheric mantle and lower crustal materials and the formation of the CMTZ we observe now.

Recent studies (Barnes 1997) have demonstrated that the solidification temperature of the upward propagating magma can be significantly reduced if water exists in the lithospheric mantle. These studies also indicate that the magma solidification temperature in the crust is approximately the same as the temperature of the Moho surface in continental cratonic areas. So in dynamics, materials in the CMTZ show not only deformation features but also flow characteristics reflected by the fluid–melt bodies in it. In thermodynamics, heat exchange can be realized not only through heat conduction but also by convection induced by fluid–melt flow, and its transitional patterns are mainly caused by the transfer of mantle magma. By using the concept of a nonlinear porosity wave in a deformation porous medium (e.g. Richter and Mckenzie (1984), Barcilon and Richter (1986) and Mckenzie (1987)), a conceptual model of the formation of the CMTZ can be set up (figure 7) (Zhao *et al* 2005). At the initial stage of the CMTZ formation in the intercontinental plate ( $t = t_0$ ), since the bottom of the lithosphere suffers the driving influences of temperature and floatage from the asthenosphere, partial melts in the lithospheric mantle ascend and the magma pressure increases under the initially relatively impermeable thin Moho layer. Once the increased magma pressure exceeds the material strength of the impermeable thin layer, the accumulated magma bursts out and penetrates the thin layer; consequently the channel in which magma goes through the thin layer is opened and it releases the magma pressure underneath the thin layer ( $t = t_1$ ). The magma can travel some distance upwards under the control of the ground temperature field until it becomes solidified. The solidification of the ascending magma can generate a new upward impermeable thin layer above the initial Moho surface, which leads to a further rise in the Moho surface. At the same time, the expanded pores of the underlying material of the initial impermeable layer may become consolidated and



**Figure 7.** The conception model of formation of CMTZ (after Zhao *et al* (2005)). (a)  $t = t_0$ : Moho of a thin impermeable layer leads to the pressure increase underneath the layer. (b)  $t = t_1$ : the thin impermeable layer collapses due to underneath pressure increase. (c)  $t = t_2$ : formation of a new upward thin layer leads to the rise of Moho, while the formation of a new downward thin layer results in the downward movement of the crustal material.

closed due to the release of the magma pressure and magma. As a result, a new downward impermeable layer is generated under the initial Moho surface ( $t = t_2$ ). The generation of the new upward and downward impermeable layers marks the formation of the porosity wave. Correspondingly the Moho surface moves upwards, while the crustal material on the initial Moho surface moves downwards. Also, the nonlinear porosity wave travels upwards as its propagating direction is consistent with the movement direction of magma. The generation and propagation of the nonlinear porosity wave cannot be stopped until the whole lithosphere system arrives at a new balanced condition. The upward and downward movement of the newly generated thin layer gives rise to the formation and evolvement of a mantle–crust transition layer in

the intercontinental plate. According to this new conceptual model, the formation and evolution of the CMTZ could be investigated in a quantitative way.

## Acknowledgments

This study is supported financially by the Chinese Ministry of Science and Technology (no 2002CB412601), Natural Science Foundation of China (no 40230056) and the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCX-03-02 and 030513).

## References

- Alsdorf D, Brown L, Nelson K D, Makovsky Y, Klemperer S and Zhao W 1998 Crustal deformation of the Lhasa Terrane, Tibet Plateau from Project INDEPTH deep seismic reflection profiles *Tectonics* **17** 501–19
- Barcion V and Richter F M 1986 Nonlinear waves in compacting media *J. Fluid Mech.* **164** 429–48
- Barnes H L 1997 *Geochemistry of Hydrothermal Ore Deposits* (New York: Wiley)
- Boudier A and Bouchez J L 1980 Interpretation of perioditic structures from ophiolitic and oceanic environments *Am. J. Sci.* **280** 192–210
- Carbonell R, Gallart J and Perez-Estaun A 2002 Modelling and imaging the Moho transition: the case of the southern Urals *Geophys. J. Int.* **149** 134–48
- Chen S H, O'Reilly S Y, Zhou X H, Griffin W L, Zhang G H, Sun M, Feng J Q and Zhang M 2001 Thermal and petrological structure of the lithosphere beneath Hannuoba, Sino-Korean Craton, China: evidence from xenoliths *Lithos* **56** 267–301
- Christensen N I 1989 Reflectivity and seismic properties of the deep continental crust *J. Geophys. Res.* **94** 17793–804
- Cogan M J, Nelson K D, Kidd W S F, Wu C and Project INDEPTH team 1998 Shallow structure of the Yadong-Gulu rift, southern Tibet, from refraction analysis of Project INDEPTH common midpoint data *Tectonics* **17** 46–61
- Cox K G, Charnley N, Gill R C O and Parish K A 1993 Alkali basalt from Shugra, Yemen: magmas generated in the crust–mantle transition zone? *Magmatic Processes and Plate Tectonics* (Geological Society of London Special Publication no 76) ed H M Pritchard, A Alabaster, N B W Harris and C R Neary (London: Geological Society) pp 443–53
- Curtis A, Trampert J, Snieder R and Dost B 1998 Eurasian fundamental mode surface wave phase, velocities and their relationship with tectonic structure *J. Geophys. Res.* **103** 26919–47
- Deng W M and Zhong D L 1997 Crust–mantle transition zone and geological evolution significance in the lithosphere *Chin. Sci. Bull.* **42** 2474–82
- Durrheim R J and Mooney W D 1994 Evolution of the Precambrian lithosphere: seismological and geochemical constraints *J. Geophys. Res.* **99** 359–74
- Fan W M, Zhang H F, Baker J, Jarvis K E, Mason P R D and Menzies M A 2000 On-craton and off-craton Cenozoic spinel peridotites in eastern China: similarity and difference *J. Petrol.* **41** 933–50
- Fountain D M and Salisburg M H 1981 Exposed cross-section through the continental crust: implications for crustal structure, petrology and evolution *Earth Planet. Sci. Lett.* **56** 263–77
- Fountain D M, Salisbury M H and Percival J A 1990 Seismic structure of the continental crust based on rock velocity measurements from the Kapuskasing uplift *J. Geophys. Res.* **95** 1167–86
- Ge W C, Lin Q, Sun D Y, Wu F Y, Won C K, Lee M, Jin M and Yun S 1999 Geochemical characteristics of the Mesozoic basalts in Da Hingan Ling: evidence of the mantle–crust interaction *Acta Petrologica Sin.* **15** 397–407
- Griffin W L and O'Reilly S Y 1987 The composition of the lower crust and the nature of the continental Moho xenolith evidence *Mantle Xenoliths* ed P H Nixon (Chichester: Wiley) pp 413–30
- Griffin W L, Zhang A D, O'Reilly S Y and Ryan C J 1998 Phanerozoic evolution of the lithosphere beneath the Sino-Korean Craton *Mantle Dynamics and Plate Interactions in East Asia* (*Am. Geophys. Union, Geodyn. Ser.* vol 27) ed M F J Flower, S L Chung, C H Lo and T Y Lee (Washington, DC: American Geophysical Union) pp 107–26
- Guo F, Fan W M, Wang Y J and Lin G 2001 Late Mesozoic mafic intrusive complexes in the North China Block: constraints on the nature of subcontinental lithospheric mantle *Phys. Chem. Earth A* **26** 759–71
- Guo F, Fan W M, Wang Y J and Lin G 2003 Geochemistry of late Mesozoic mafic magmatism in west Shandong Province, eastern China: characterizing the lost lithospheric mantle beneath the North China Block *Geochem. J.* **37** 63–77
- Hall J, Quinlan G, Marillier F and Keen C 1990 Dipping shear zones and the base of the crust in the Appalachians, offshore Canada *Seismic Probing of Continent and their Margins* ed J H Leven, D M Finlayson, C Wright, J C Dooley and B L N Kennett *Tectonophysics* **173** 581–93
- Hauser E C, Gephart J, Latham T, Oliver J, Kaufman S, Brown L and Lucchitta I 1987 COCORP Arizona transect: strong crustal reflections and offset Moho beneath the transition zone *Geology* **15** 1103–6
- Hermann J, Muntener O and Gunther D 2001 Differentiation of Mafic magma in a continental crust-to-mantle transition zone *J. Petrology* **42** 189–206
- Holbrook W S, Mooney W D and Christensen N I 1992 The seismic velocity structure of the deep continental crust *Continental Lower Crust* (*Developments in Geotectonics* vol 23) ed D M Fountain, R Arculus and R W Kay (New York: Elsevier) pp 1–34
- Holloway J R and Wood B J 1988 *Simulating the Earth, Experimental Geochemistry* (Boston: Unwin Hyman)
- Jarchow C M and Thompson G A 1989 The nature of the Mohorovicic discontinuity *Ann. Rev. Earth Planet. Sci.* **17** 475–506
- Jousselin D and Nicolas A 2000 The Moho transition zone in the Oman ophiolite–relation with wehrlites in the crust and dunites in the mantle *Mar. Geophys. Res.* **21** 229–41
- Lin G, Wang Y H, Guo F, Wang Y J and Fan W M 2004 Geodynamic modelling of crustal deformation of the North China block: a preliminary study *J. Geophys. Eng.* **1** 63–9
- Mckenzie D 1987 The compaction of igneous and sedimentary rocks *J. Geol. Soc. Lond.* **144** 299–307
- Meissner R and Mooney W 1998 Weakness of the lower continental crust: a condition for delamination, uplift and escape *Tectonophysics* **296** 47–60
- Melhuish A, Holbrook S W, Davey F, Okaya D A and Stern T 2005 Crustal and upper mantle seismic structure of the Australian Plate, South Island, New Zealand *Tectonophysics* **395** 113–35
- Menzies M A, Fan W M and Zhang M 1993 Paleozoic and Cenozoic lithosphere, Sino Korean Craton, China *Magmatic Processes and Plate Tectonics* (Geological Society of London Special Publication vol 76) pp 71–84
- Mooney W D and Meissner R 1992 Multigenetic origin of crustal reflectivity: a review of seismic reflect: on profiling of the continental lower crust and Moho *Continental Lower Crust* (*Developments in Geotectonics* vol 23) ed D M Fountain, R Arculus and R W Kay (New York: Elsevier) pp 45–80
- O'Reilly S Y and Griffin W L 1996 4-D lithosphere mapping: methodology and examples *Tectonophysics* **185** 67–82
- Owens T J and Zandt G 1997 Implication of crustal property variations for models of Tibetan Plateau evolution *Nature* **387** 37–43



- Peter A Z and Sierd C 2004 Dynamic processes controlling evolution of rifted basins *Earth-Sci. Rev.* **64** 1–50
- Richter F M and McKenzie D 1984 Dynamical models for melt segregation from a deformable matrix *J. Geol.* **92** 729–40
- Ringwood A E 1975 *Composition and Petrology of the Earth's Mantle* (New York: McGraw Hill)
- Royden L H, Burchfiel A C, King R W, Wang E, Chen Z, Shen F and Liu Y 1997 Surface deformation and lower crustal flow in eastern Tibet *Science* **276** 788–90
- Sandmeier K J, Waelde W and Wenzel F 1988 Physical properties and structure of the lower crust revealed by one and two dimensional modeling *Geophys. J. R. Atmos. Soc.* **89** 339–44
- Sandvol E, Ni J, Kind R and Zhao W 1997 Seismic anisotropy beneath the Southern Himalayan–Tibet collision zone *J. Geophys. Res.* **102** 17813–23
- Snyder D B and Flack C A 1990 A Caledonian age for reflection in mantle lithosphere, north and west Scotland *Tectonics* **9** 903–22
- Stefano R D, Chiarabba C, Lucente F and Amato A 1999 Crustal and uppermost mantle structure in Italy from the inversion of P-wave arrival times: geodynamic implications *Geophys. J. Int.* **139** 483–98
- Teng J W, Zhang Z J and Bai W M 2003 *Physics of the Lithosphere in China* (Beijing: China Science Press)
- Wang Y, Houseman G A, Lin G, Guo F, Wang Y J, Fan W M and Chang X 2005 Mesozoic lithospheric deformation in the North China block: numerical simulation of evolution from orogenic belt to extensional basin system *Tectonophysics* **405** 47–63
- Wenzel F, Sandmeier K J and Waelde W 1987 Properties of the lower crust from modeling refraction and reflection data *J. Geophys. Res.* **92** 11575–83
- Willett S D and Beaumont C 1994 Subduction of Asian lithospheric mantle beneath Tibet inferred from models of continental collision *Nature* **369** 642–645
- Xu Y G 2001 Thermo-tectonic destruction of the Archean lithospheric keel beneath the Sino-Korean craton: evidence, timing and mechanism *Phys. Chem. Earth (Part A)* **26** 747–57
- Xu Y G, Menzies M A, Matthey D P, Lowry D, Harte B and Hilton R W 1996 The nature of lithospheric mantle near the Tancheng-Lujiang fault, China: an integration of texture, chemistry and O isotopes *Chem. Geol.* **134** 67–81
- Zhang H F, Sun M, Zhou X H, Zhou M F, Fan W M and Zheng J P 2003 Secular evolution of the lithosphere beneath the eastern North China craton: evidence from Mesozoic basalts and high-Mg andesites *Geochim. Cosmochim. Acta* **67** 4373–87
- Zhang Z J, Badal J, Li Y K, Chen Y, Yang L Q and Teng J W 2005 Crust–upper mantle seismic velocity structure across Southeastern China *Tectonophysics* **395** 137–57
- Zhang Z J, Li Y K, Lu D Y, Teng J W and Wang G J 2000a Velocity and anisotropy structure of the crust in the Dabieshan orogenic belt from wide-angle seismic data *Phys. Earth Planet. Inter.* **122** 115–31
- Zhang Z J, Wang G, Teng J and Klempner S 2000b CDP mapping to obtain the fine structure of crust and upper mantle from seismic sounding data: an example in the Southeastern China *Phys. Earth Planet. Inter.* **122** 133–46
- Zhao C B, Hobbs B E, Ord A, Lin G and Muhlhaus H B 2005 Theoretical and numerical analysis of large-scale heat transfer problems with temperature-dependent pore-fluid densities *Eng. Comput.: Int. J. Comput.-Aided Eng.* **22** 232–52